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# PHOTOVOLTAIC FIELD-INDUCED SELF-PHASE MODULATION IN LIQUID CRYSTAL CELLS (PREPRINT)

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**14. ABSTRACT**
We show that photovoltaic fields generated internally in $LiNbO_3$:Fe substrates are capable of efficiently reorienting liquid crystal molecules leading to new concepts of optically addressable light modulators. Using an arrangement consisting of a liquid crystal layer in contact with one or more $LiNbO_3$:Fe photovoltaic substrates, we observe spatial filtering due to self-phase modulation in a planar oriented cell. The $LiNbO_3$:Fe substrates are arranged such that light propagates along the +c axis, allowing a secondary process of power transfer to occur through photore-fractive contra-directional two-beam coupling.

**15. SUBJECT TERMS** Photovoltaic, Substrate, Liquid Crystal, Two-Beam Coupling, Spatial Filtering

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## I. INTRODUCTION

$LiNbO_3$:Fe is capable of producing a bulk electric field on the order of 140 kV/cm [1]. Upon illumination, an asymmetrical potential associated with this material causes photoionized electrons to move in a preferential direction. This flow of electrons in one direction gives rise to a photoinduced current and a subsequent electric field in the region of light known as the photovoltaic (PV) field [2]. We have demonstrated a liquid crystal (LC) arrangement which uses the PV field generated in $LiNbO_3$:Fe substrates to reorient LC molecules [3]. When illuminated, the PV field in each substrate creates a field across the LC layer sufficient to reorient the LC molecules. The cell can be oriented with planarly aligned LC molecules to create a hybridized (organic/inorganic) spatial filter, which reduces the intensity of the transmitted light through a transverse phase modulation of the beam resulting in a lensing effect. The cell can also be arranged with a LC layer between a $LiNbO_3$:Fe substrate and either an indium tin oxide (ITO) coated or uncoated glass substrate. The ITO coated glass substrate acts as a virtual ground to the surface charges on the $LiNbO_3$:Fe substrate, creating a field across the LC layer. When the cell is constructed with an uncoated glass substrate, the PV field from the $LiNbO_3$:Fe substrate penetrates into the LC layer resulting in a reorientation of the LC molecules.

In addition to being PV, $LiNbO_3$:Fe is also a photorefractive material. This allows contra-directional two-beam coupling (TBC) to take place when two mutually coherent counter-propagating beams couple through a reflection grating [4–6]. Power transfer occurs in a single direction determined by the signs of the charge carriers and the effective electro-optic coefficient for a given crystal orientation [7]. In the self-pumped TBC configuration, the pump beam propagates along the $+c$ axis and a transfer of power occurs between the pump beam and a Fresnel reflection generated signal beam from the rear surface of the crystal; this effect has been observed experimentally in $LiNbO_3$:Fe [8–10]. To take advantage of the photorefractive effect, the $LiNbO_3$:Fe substrates are oriented such that the signal beam is amplified at the expense of the pump beam. This allows TBC to take

place in each substrate while the PV field simultaneously reorients the LC.

## II. EXPERIMENTAL DESCRIPTION

The $LiNbO_3$:Fe substrates used for this study were $25.4 \times 25.4 \times 1.0\,mm^3$ and were doped with 0.05 molar % $Fe_2O_3$. The thickness of the crystal along *c* axis was 1.0 mm and the *c* surfaces of each crystal were optically polished. The substrates enclosing the LC layer were spin coated with a rubbing layer consisting of a mixture of 0.125 wt.% Elvamide® in methanol and rubbed for planar alignment. Elvamide is a methanol soluble nylon multipolymer resin (DuPont). Each cell was constructed using 20 μm spacers and filled with TL205 (Merck), a highly resistive low ionic LC that has an ordinary index of 1.527 and a $\Delta n$ of 0.217 at 589 nm and 20°C [11]. This LC was chosen in order to reduce the effects of screening charges that may result from a more ionic LC. The cells were constructed with the substrates enclosing the LC layer rubbed anti-parallel with respect to one another. To investigate the TBC processes in the substrates, data were also taken in the absence of the LC. For these experiments, the cell was filled with an index matching fluid of $n = 1.7$, closely matching the extraordinary index of TL205. The index matching fluid simulated any reduction in etalon effects resulting from the presence of the LC.

The experimental arrangement is shown in Figure 1. The pump beam, originating from a continuous wave 532 nm intracavity frequency doubled $YVO_4$:Nd laser (Coherent Verdi-5), was focused within the LC layer at an optimum position yielding the fastest response time. The pump beam propagated along the $+c$ axes of the $LiNbO_3$:Fe substrates and was focused at ≈f/30, f/15, or f/4.8, yielding 1/e diameters at the focal plane as seen in Table 1. The *c*-axis absorption coefficients at 532 nm were approximately $1.53\,cm^{-1}$ for each $LiNbO_3$:Fe

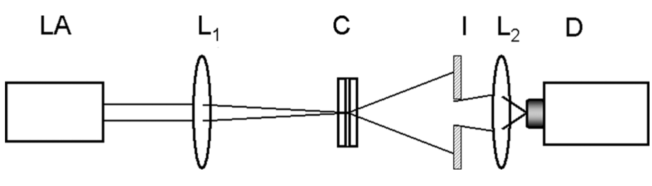


**FIGURE 1** Experimental arrangement used for testing hybridized organic/inorganic spatial filter. The pump beam, originating from a 532 nm laser (LA), was focused onto the cell (C) using a plano-convex lens ($L_1$). The transmitted power through a cone angle determined by the iris (I) was focused onto the detector (D) using a collection lens ($L_2$).

**TABLE 1** Experimental Parameters for Each f-number Used to Test Hybridized Spatial Filters

| F-number | Lens focal length (mm) | Spot size (μm) |
|---|---|---|
| f/30 | 100 | 20.3 |
| f/15 | 50 | 10.2 |
| f/4.8 | 16 | 3.3 |

substrate. A photodiode placed behind the cell and an oscilloscope were used to monitor the transmitted laser power for a 5.5 degree full cone angle.

## III. EXPERIMENTAL RESULTS

### $LiNbO_3$:Fe Substrates

Results for the transmitted power of the hybridized spatial filter constructed with a LC layer enclosed by two $LiNbO_3$:Fe substrates at f/30, f/15, and f/4.8 are shown in Figures 2a, 2b, and 2c, respectively (solid curves). In the absence of the LC, a steady decrease in transmitted power is seen as a result of TBC in the photorefractive substrates (dotted curves). However, the addition of the LC yields a much more dramatic initial response as a rapid reduction in transmitted power for a 5.5 degree cone angle is initially observed. This is attributed to a lensing effect that occurs as a result of the Gaussian profile of the incident beam intensity. A build up of charges on the surfaces of the $LiNbO_3$:Fe substrates is generated by the PV field in each substrate. As depicted in Figure 3a, the build up of charges and the subsequent field across the LC layer is initially strongest in the center of the Gaussian beam where it is most intense. As a result of the Gaussian profile, the liquid crystal molecules at the center of the beam are influenced more by the field than those at the edges of the beam. Because the LC molecules are reoriented to varying degrees across the inhomogeneous region of illumination, the incident light experiences a graded index of refraction. A transverse phase modulation of the beam occurs and the LC acts as a lens to strongly diverge the beam, which is perceived as a decrease in the transmitted power reaching the detector. However, as the surface charges gradually build up over time in the less intense edges of the beam, a further reorientation of the LC molecules is induced throughout the illuminated region. As depicted in the steady-state regime of Figure 3a, this results in a loss of the graded index of refraction, thereby disrupting the lensing effect and

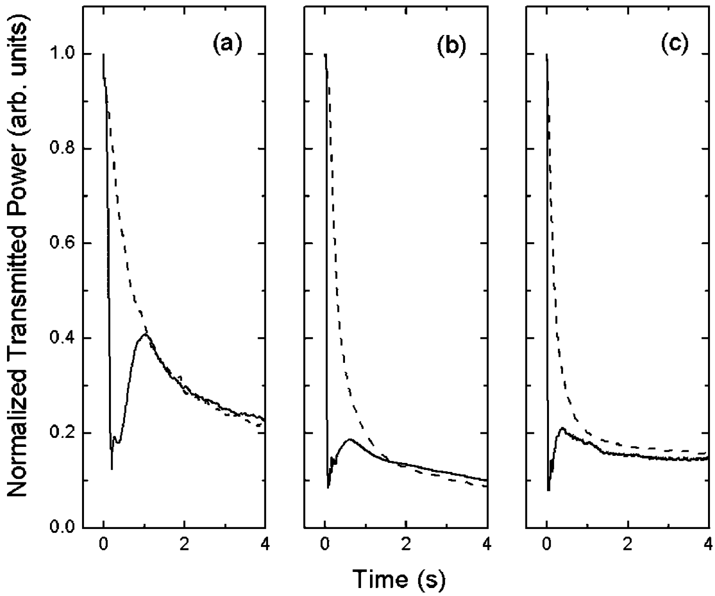


**FIGURE 2** The normalized transmitted power for a 5.5 degree cone angle for the hybridized spatial filter constructed with a LC layer enclosed by two $LiNbO_3$:Fe substrates at (a) f/30, (b) f/15, and (c) f/4.8. The transmitted power in the absence of the LC (dotted curve) and in the presence of the LC (solid curve) is shown.

reducing the divergence of the transmitted beam. The transmitted power of the hybridized cell increases to that of the empty cell, and any further reduction in transmitted power is a result of the TBC occurring in the $LiNbO_3$:Fe substrates.

Although the TBC process is secondary to that of the phase modulation, it is still useful to investigate what portion of the observed reduction in intensity is from power coupling in the photorefractive substrates and what portion originates from divergence due to the lensing effect. The characteristics of the power coupling can be investigated by collecting all of the diverged light exiting the cell and focusing it into the detector. Due to the large divergence angles experienced by the beam, it is difficult to collect all of the light simply by using a collection lens. Instead, an opal diffuser was placed immediately behind the cell, as seen in Figure 4. Acting like an integrating sphere, the diffuser collected all of the diverged light and created a Lambertian intensity response regardless of the exiting divergence angle. Without the divergence preventing light from reaching the

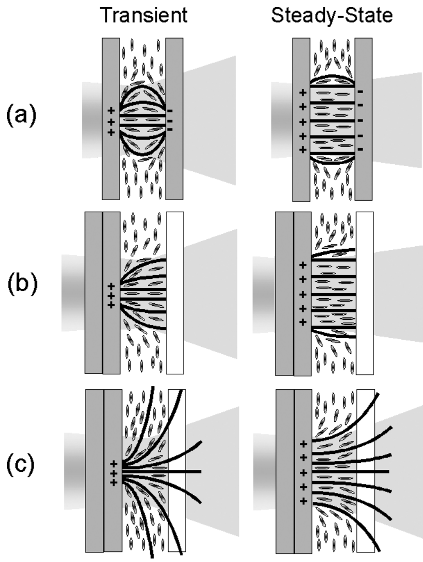


**FIGURE 3** The transient and steady-state LC molecule orientations for cells constructed with a LC layer enclosed by (a) two $LiNbO_3$:Fe substrates, (b) two $LiNbO_3$:Fe substrates and an ITO coated glass substrate, and (c) two $LiNbO_3$:Fe substrates and an uncoated glass substrate. The $LiNbO_3$:Fe substrates are shaded and the glass substrates are white. The shaded region represents the portion of the cell illuminated by a laser beam propagating from left to right.

detector, any observed reduction in intensity is a result of TBC in the substrates. The characteristics of an empty cell were first observed. Without changing the position of the cell with respect to the diffuser, it was then filled with TL205, and the characteristics were measured once again. As shown in Figure 4, there is a reduction in the power coupling when the LC layer is present, which is attributed to a disruption in the beam profile due to the strong divergence induced by the LC layer. This disruption of the beam prevents an efficient grating from being established in the second $LiNbO_3$:Fe substrate. The second substrate is useful in creating a field across the LC layer, but it does not significantly contribute to any power coupling occurring in the cell.

## $LiNbO_3$:Fe and Glass Substrates

Because the second $LiNbO_3$:Fe substrate mainly serves to assist in the development of a field across the LC, it can be replaced by an

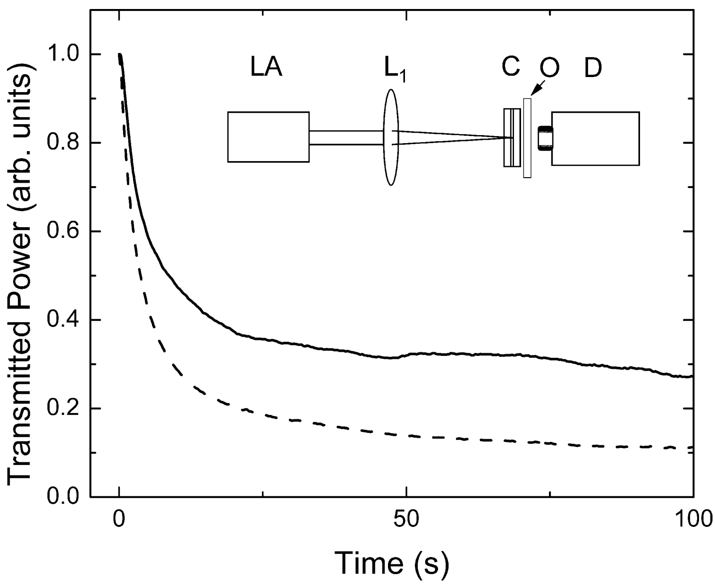


**FIGURE 4** Experimental arrangement used for investigating the TBC in each substrate. The pump beam, originating from a 532 nm laser (LA), was focused onto the cell (C) using a plano-convex lens ($L_1$). An opal diffuser (O) was placed in front of the detector (D). The transmitted power for an empty cell (dotted curve) and a cell filled with TL205 (solid curve) are shown.

ITO coated glass substrate. With the cell arranged such that the ITO coating is in contact with the LC layer, the ITO coating acts as a virtual ground for the PV field generated in the first $LiNbO_3$:Fe substrate; thus creating a field across the LC layer. To maintain the same maximum possible contribution due to TBC, the second $LiNbO_3$:Fe substrate was added to the front of the cell in direct contact with the first $LiNbO_3$:Fe substrate. The transmitted power for this cell at f/30, shown in Figure 5, is similar to that in Figure 2a for a LC layer enclosed by two $LiNbO_3$:Fe substrates, although with a stronger reduction in transmitted power because of the increased efficiency of the TBC in the substrates. As depicted in Figure 3b, the field across the LC creates a graded index of refraction that initially diverges the output light in the transient regime. As the surface charges build up in the region of light, the graded index is lost and the performance of the cell approaches that of the empty cell. A further reduction in power once the lensing effect has reached a steady-state is a result of TBC in the $LiNbO_3$:Fe substrates.

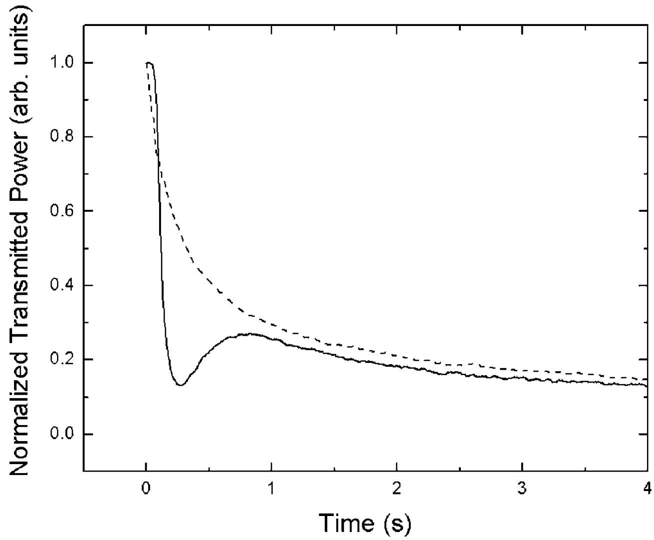


**FIGURE 5** The normalized transmitted power for a 5.5 degree cone angle for the hybridized spatial filter constructed with a LC layer enclosed by a $LiNbO_3$:Fe substrate and an ITO coated glass substrate at f/30. The transmitted power in the absence of the LC (dotted curve) and in the presence of the LC (solid curve) is shown.

The cell can also be constructed using an uncoated glass substrate in place of the ITO coated substrate. For this configuration, the PV field created in the $LiNbO_3$:Fe substrate must penetrate into the LC layer, as depicted in Figure 3c. The transmitted power at f/30, f/15, and f/4.8 is shown in Figures 6a, 6b, and 6c, respectively. When the PV field reorients the LC molecules, a graded index is created and the light is diverged. However, as depicted in Figure 3c, the build up of surface charges will modify the graded index, but because there is no corresponding field in the second substrate, there is no build up of surface charges to create a more homogeneous field throughout the region of illumination. Although there is a slight increase in the transmitted power reaching the detector as a result of the modification of the graded index, the field across the liquid crystal remains inhomogeneous and the divergence of the beam is not completely lost in the steady-state. As a result, the transmitted power does not increase to that of the empty cell as it did for the previous cell constructions. The TBC process in the $LiNbO_3$:Fe substrates continues to reduce the transmitted power after the orientation of the LC molecules has reached a steady-state.

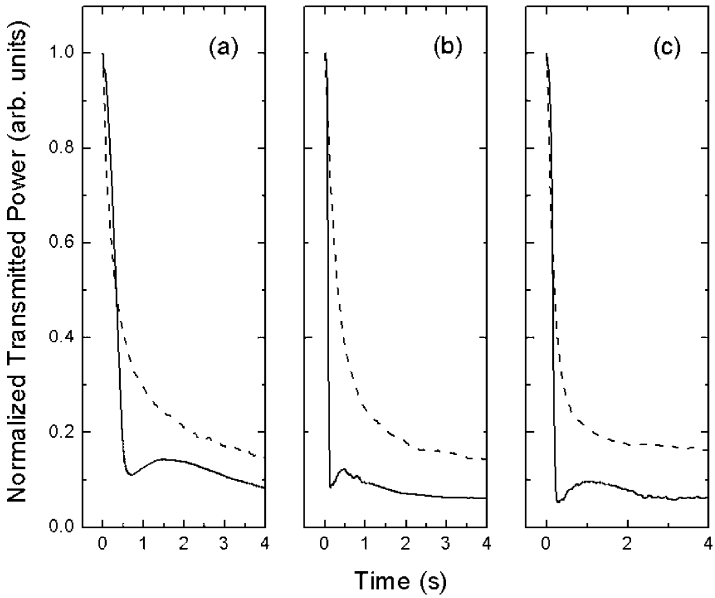


**FIGURE 6** The transmitted power for a 5.5 degree cone angle for the hybridized spatial filter constructed with a LC layer enclosed by a $LiNbO_3$:Fe substrate and an uncoated glass substrate at (a) f/30, (b) f/15, and (c) f/4.8. The transmitted power in the absence of the LC (dotted curve) and in the presence of the LC (solid curve) is shown.

## IV. CONCLUSIONS

The PV field in $LiNbO_3$:Fe substrates is capable of efficiently reorienting LC molecules without the application of an external electric field. When the LC layer is in contact with two $LiNbO_3$:Fe substrates, or a $LiNbO_3$:Fe substrate and an ITO coated glass substrate, the LC molecules in the region of illumination are reoriented by the resulting field created across the cell. The incoming laser beam experiences a transverse phase modulation and it is strongly diverged. However, with the build up of surface charges on the $LiNbO_3$:Fe substrates, the phase modulation and subsequent beam divergence is disrupted in the steady-state. When the cell is constructed with the LC layer in contact with a $LiNbO_3$:Fe substrate and an uncoated glass substrate, the PV field penetrates into the LC layer to induce a transverse phase modulation of the beam. In this case, the buildup of surface charges results in only a slight disruption of the transverse phase modulation and subsequent divergence of the beam.

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